ATMOSPHERIC MODELING, FIELD PROGRAMS, AND DECISION SYSTEMS

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ABSTRACT*

The interrelation between field programs and atmospheric modeling is discussed in the context of studies of weather modification. In particular, numerical models of convective clouds are considered. It is shown how activities in both field programs and modeling affect decisions concerning each other, culminating in the use of models for day-to-day "go" and "no go" decisions concerning the field programs. Illustrations are given from work done at RAND and elsewhere. A few typical results from the RAND cumulus dynamics model are presented.

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I

It was something of a surprise to me to find myself scheduled to talk on the role of modeling and decision systems, for that appears to involve close coupling of field programs with modeling, and I have had no direct connection with a field program. But, as I hope to make clear, there is always such a connection, whether direct or indirect, and it is of utmost importance to both activities. The modeler must be strongly concerned with field programs even if he does not engage in them himself. I am glad that our moderator said that there was little distinction between the topics for yesterday afternoon and this morning, for my subject is the interrelation between field programs and modeling as it is expressed in decision making.

We have already heard many good reasons for engaging in modeling along with field programs. One of those reasons is to use models to help make decisions concerning the field programs. In its most evident application this can mean using a model the way the Experimental Meteorology Laboratory does in Miami,[1,2] or the way the MRI group does in Arizona[3] -- to determine which clouds are the best for seeding or which days are the most favorable. But this usage may come rather late in the scheme of things. Actually, decisions must be made all along the line, both on the modeling and on the field-program sides, and simultaneous activity on both sides offers the best hope of success.

Both field programs and modeling may be divided into "development" and "production" stages, although those words may have somewhat different connotations in different contexts. In the context of the present meeting, the "development" stage of a field program could include observations of clouds to learn more about the processes going on in them, and it could also include experimental attempts at modification. Later, when we have developed a reasonably good knowledge of the results of certain modification activities, we can move to the "production" stage and engage in these activities for practical reasons, such as increasing rainfall or snowfall in a particular region. In some programs, the "production" stage could come earlier.

In the case of modeling (and I refer only to numerical modeling, though many of the same things could be said for laboratory modeling), the "development" stage covers the initial formulation and programming. It must also include some type of check to determine what relation the results bear to reality. Here is the first obvious spot where a field program can exercise a decision-making influence on a model. The checking of model results against actual observations tells us whether we are on the right track in our model building and suggests changes to be made in the model. I will have more to say about this kind of checking later. At this stage, decision-making can go in the opposite direction, too, for the characteristics of the model under consideration may suggest the types of observations that are most useful. Frequently in developing a model one is confronted with the need to know the value of a quantity that is not or cannot be observed. Sometimes theory will suggest an observable substitute quantity, but at other times the field experimenter is spurred to develop new equipment or new uses for old equipment to satisfy the modeler.

Only after thorough checking of the model results against actual observations can the "production" stage of a model be entered. One aspect of this stage is the operational use of a model for day-to-day implementation of the field program, as mentioned previously. Another aspect is the use of the model itself in the direct study of the thing being modeled.

Atmospheric processes are extremely complex, and one of the functions of both field experimentation and modeling is to render the complexity more intelligible. Many of the processes are not well understood, which makes the design of the model or experiment difficult, but frequently a well-designed model will lead us to an understanding of such processes. The particular advantage of a model in this respect is its ability to isolate the effects of individual processes or parameters. This was discussed yesterday by Orville. It is easy to run through a series of numerical experiments, varying one component of the model to see how this affects the total results. However, if this is to be more than a mathematical exercise, it must be tied to observations of the real atmosphere. Hence, modeling must not proceed independent of field experimentation. On the other hand, a field program not based on the understanding of theory that comes from modeling could flounder and produce great masses of undigestible data. The implicitness of atmospheric processes makes it virtually impossible for a field program to study one process in isolation; hence the recourse to models.

Thus, we see that models and field programs should each contribute to decisions concerning the other in their earliest stages of development. Throughout the process, decisions concerning the direction of work on a model should be based on field observations as much as on theory. Once a model achieves a fair degree of realism, even if only in one respect, such as the ultimate height of convection, it can be used as a basis for routine day-to-day decisions about field operations. At a higher degree of development, the model can be used to study the atmosphere directly, but still with continual verification from field observation.

II

In the many interactions that I have touched upon, the flow of information between the experimenter and the theoretician may be extremely complex. When both are represented in a combined operation, matters are simplified. A good example of such a combined operation is the Experimental Meteorology Laboratory. The flow of information may, however, be largely through the literature. A good example of this is the parameterization of cloud microphysics by Kessler. There is a great deal of knowledge available concerning the theory of microphysical processes in clouds, and several numerical models have been developed to describe the changes in the drop-size spectrum. Concurrently, models have been constructed to describe the dynamics of whole clouds, but because of a gross mismatch of both time and space scale, these types of models have not yet successfully been combined. What was needed was a parameterization whereby the microscale processes could be described with reasonable accuracy in terms of cloud-scale parameters. Making full use of observations from field and laboratory experiments quoted in the literature, together with physical theory, Kessler produced the required parameterization for three of the most important microphysical processes.[4,5] Upon its publication, this parameterization was picked up by many cloud modelers and incorporated into their own models, often with variations, such as the alternate expression for conversion proposed by Berry.[6] The incorporation of this parameterization has so improved the models that most of them now contain it or something very much like it. That the models were improved has been verified by field observation.

III

The ultimate use to which a model will be put determines to a large extent what kind of model it will be. If the model is to be a general research tool, designed to reveal new information about the workings of the atmosphere, it must be as comprehensive as possible. Ideally this would mean going back to the basic equations of hydrodynamics, thermodynamics, physics, etc., to describe all possible processes, and solving these equations without approximation. This is an unattainable goal on several counts. Compromises must be made all along the line. However, it is possible to specialize the equations to a particular scale of motion (thereby simplifying them significantly), parameterize the interaction with other scales, and solve them by numerical methods. Even with drastic pruning, such a model is usually found to tax the capabilities of the largest and most advanced computers permitted by the existing technology. Cloud models fitting this description have been in use now for nearly ten years, and their requirements have always kept pace with, or remained slightly ahead of, whatever computational facilities have been available. As the computers grew, so did the models. Perhaps now is the time to adopt some radically new approach, but I cannot discuss this today.

Throughout all this growth it has been necessary to tie the models to reality by extensive comparison of their results with field observations. The model discussed by Orville is of this type, and he has the field programs of the South Dakota School of Mines to work with.[7] The model I developed is also of this type, and I have had some access to the results of the field programs in the Caribbean of the Naval Research Laboratory and the Experimental Meteorology Laboratory.[8,9] Although these and other similar models have aided in the understanding of many of the facets of cloud dynamics, they are not sufficiently comprehensive to be able to supplant field programs, nor are they likely to become so. Their use, however, can suggest certain types of field programs that might be worthwhile to undertake and others that would probably be useless.

For some purposes a much more simplified model can be useful. Typically, this sort of model considers only one dimension rather than two or three, and it specifies the cloud to be of some idealized form, such as a bubble or a starting plume. A large degree of parameterization is required, not only for the microphysics, but also for processes at the larger scale. Such models tend to be deficient in dynamics and can offer little toward understanding the circulations in and around clouds. Nevertheless, they have the virtue of fast running on a small computer, and they are able to predict with considerable accuracy certain features of cloud development, notably the maximum height. These models are well suited to direct use in conjunction with a field program, as has been well demonstrated by the Experimental Meteorology Laboratory and by MRI.

IV

It seems to be *de rigeur* to talk a little about one's own program, so I will do so. I will not attempt to describe it in detail or give a lot of results, but will indicate how we try to keep it tied to reality.

At RAND we have no direct connection with a field program, and we have elected to concentrate on the large hydrodynamical models. But, as I have mentioned, such models must continually be compared with field observations to assure that they are doing what they are intended to do. One of the means we have adopted is to use only real atmospheric soundings for initial data. This somewhat complicates the results, for an idealized initial condition, such as a constant lapse rate, for example, would lead to simpler patterns for all the variables. But we think that the closer correspondence to what is observed in nature is worth the added complication. In choosing the initial sounding we attempt to find conditions for which verifying data are available. This has generally meant using Caribbean soundings for days on which the instrumented aircraft of the Naval Research Laboratory or the Experimental Meteorology Laboratory were active. Even so, the verifying data can never be as extensive as we would like. The best we can usually hope for is a few penetrations showing liquid water content and temperature, together with height of base and top of the cloud and cloud width. The age of the cloud being observed is seldom known, so the choice of a time step in the simulation is somewhat arbitrary. Temperatures and dew points are hard to compare, for the model works with departures from the basic state, and that basic state cannot well be observed in practice. A most unfortunate circumstance is that the aircraft are not well able to measure horizontal and vertical components of wind throughout the cloud.

Nevertheless, we have been able to get a fair amount of data for comparison. As an illustration, Figure 1 shows a comparison of computations with four clouds observed by NRL aircraft near Puerto Rico on one day. As I have mentioned, the correspondence of temperature departure and dew point is not good, but this is related to the diffi-

Property	Cloud A	Cloud B	Cloud C	Cloud D	Notes
Height of penetration (ft)	6,600	7,100	7,350	7,700	
Temperature departure (^oC)	-0.6	-1.0	-1.2	-2.2	a
(inside temperature minus	1.8	-1.1	0.0	-1.0	b
outside temperature)	1.5	1.5	1.3	1.2	c
Evaporator dew point (^oC)	13.3	13.5	12.8	10.6	a
	16.9	15.8	13.8	9.0	b
	16.5	16.0	15.8	15.5	c
Liquid water cont nt (g m^{-3})	2.0	2.3	2.3	1.2	d
	1.4	2.2	0.0	1.2	e
	2.1	2.1	1.5	0.6	b
	2.0	2.4	2.6	3.0	c
Width of cloud (m)	1,200	600	1,000	900	a
	1,070	1,040	430	120	b
	610	790	910	910	c
Height of cloud base (ft)	2,800	2,800	2,800	2,800	a
	3,200	3,200	3,200	3,200	b
	3,200	3,200	3,200	3,200	c
Height of cloud top (ft)	~10,000	~10,000	~10,000	~10,000	a
	7,900	7,900	7,900	7,900	b
	9,100	9,100	9,100	9,100	c

a Aircraft observation.
b Computation at 20 minutes.
c Computation at 25 minutes.
d Observed by NRL total water instrument.
e Observed by Johnson-Williams liquid-water meter.

Fig. 1 -- Observed and computed values of cloud properties.

culties in relating the ages of the real and simulated clouds, lack of a proper base line, and lack of knowledge of the updrafts and downdrafts in the real clouds. I conclude from this that improvements are desirable both in the numerical model and in the observing equipment and techniques. The liquid water content shows reasonably good agreement between computation and measurement. Except for Cloud D the measurements made with the evaporation dew point equipment agree with the computations better than those made with the Johnson-Williams instrument. This is partly due to their different responses depending on drop size. But careful examination of the figures will also show a deficiency in the model related to the fact that this version had no fall-out mechanism for liquid water, and so tended toward large values at the top of the cloud and small values at the bottom. The width of the cloud, which is such an important basic input to the one-dimensional models, is of less significance here. It is somewhat dependent on the initial impulse specified, and its effect on the ultimate growth of the cloud has not been well established in this model. The height of the cloud base in the model is determined both by the initial sounding and the impulse. Hence, the experimenter has only partial control over it. The ultimate height of the cloud top can be controlled in the same way, but recent evidence indicates that the initial impulse has a rather strong effect.

A more recent version of the RAND model incorporates Kessler's parameterization of microphysics. In this version liquid water is divided into two categories: cloud water, which consists of drops small enough to move with the air, and hydrometeor water, which consists of drops large enough to fall relative to the air. Figure 2 shows how the distribution of the two forms of liquid water varies on the central axis with time. From the inception of condensation out to about 11 minutes only cloud water exists. At that time the liquid content becomes great enough to start the conversion to hydrometeor water, and both forms coexist. Around 15 minutes rain starts to fall from the base of the cloud, first reaching the ground at 22 minutes. Later the base of the cloud lifts, and by the time the

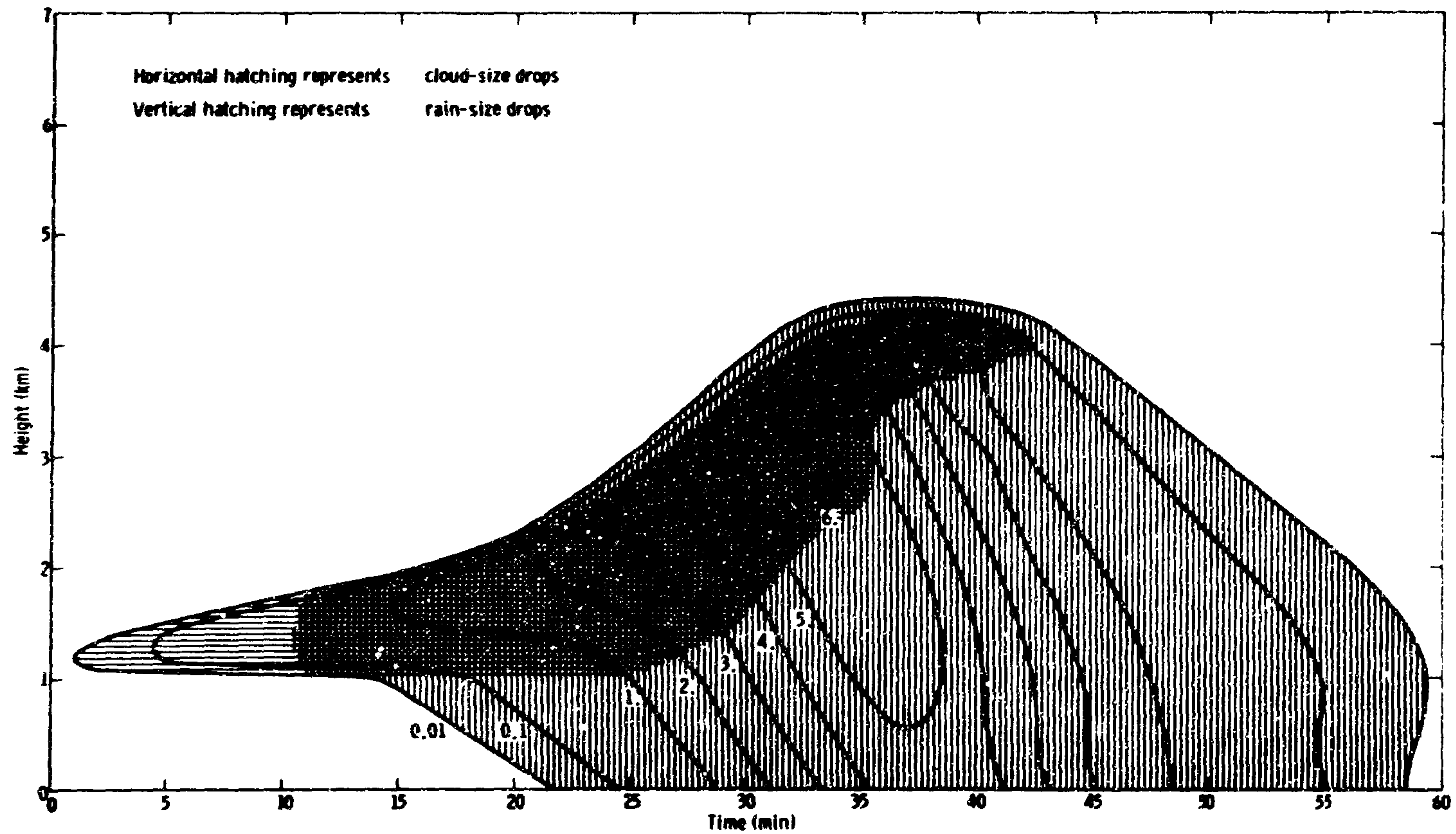

Fig. 2 -- Mixing ratio of total liquid water (g kg^{-1}) on the central axis. Horizontal hatching represents cloud water; vertical hatching represents hydrometeor water.

cloud top reaches its maximum height, the small drops are found only in the upper kilometer or two. After 45 minutes, only hydrometeor water exists, and all of it falls to the ground before 60 minutes.

The availability of quantitative values of hydrometeor water suggests the computation of a variable that has little theoretical significance in itself, but is most important in an observational program; namely, radar reflectivity. Figure 3 shows (in the dashed line) the magnitude of the maximum value of radar reflectivity. The nominal threshold for detectability is first reached at 15 minutes, after which the value grows until 34 minutes and then decreases to the threshold at 59 minutes. This corresponds with the variation in total liquid water, shown in the previous figure. The height at which the radar reflectivity reached its maximum is shown by the solid line, and the vertical range over which the radar reflectivity is large enough for nominal detectability is indicated by shading. Fortuitously, Saunders has published a study based on observations of radar reflectivity over the Caribbean within a few days of the basic sounding used on the figure. The dotted line shows that the value of maximum radar reflectivity coincided with the computed value almost exactly for nearly ten minutes, but then leveled off more quickly. The main difference is that the observed height of the maximum continuously fell, whereas that of the computation rose until just before the cloud top also reached its maximum and then fell. But in the descending stage the slopes of the computed and observed curves were almost identical, though they were separated in time by over ten minutes. The usual problem of comparison arises: there is no wholly acceptable way of relating the zero times of the computed and observed clouds, but in any case there must be a discrepancy in this example. The rates of precipitation growth match very well, and so do the rates of descent of rain, but the timing is off. We infer that the radar echo in the observed cloud first appeared when the cloud was nearing its maximum vertical growth, but it appeared somewhat earlier in the computed cloud, while there were still substantial updrafts. This may be a result of the feature of Kessler's parameterization in which the rate of conversion from cloud to hydrometeor water is a linear function

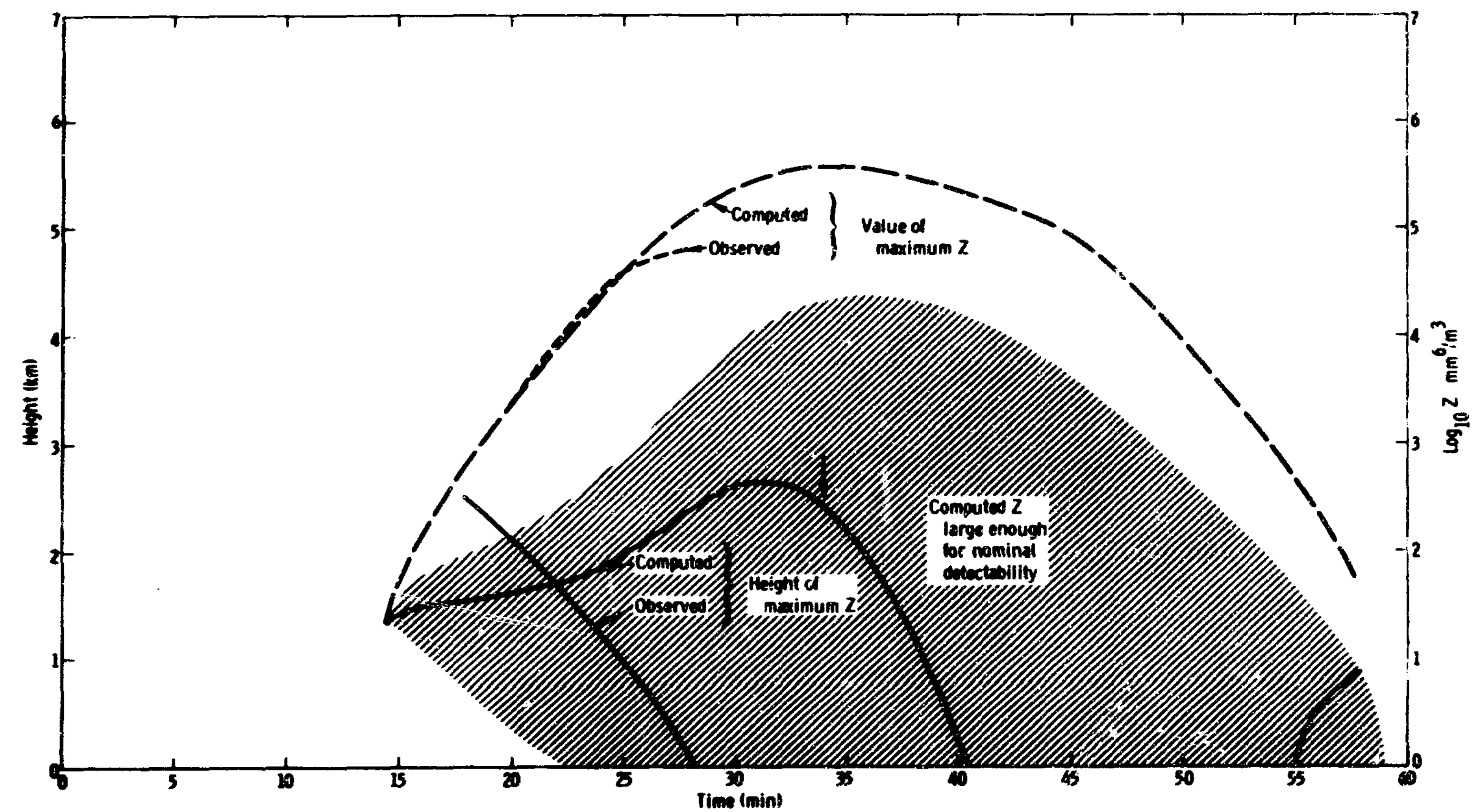

Fig. 3 -- Magnitude of maximum radar reflectivity and height range of radar reflectivity large enough for nominal detectability.

of cloud water content with a threshold. We hope to try Berry's formulation of the conversion process, and it may lead to some improvement in this respect. Beyond that lies a long series of improvements in the parameterizations and other features of the model, always comparing the response to any change with observations of real clouds. Only in that way will model building have any value in helping us to understand the complicated atmospheric processes.

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